

ILD SiW ECAL and sDHCAL dimension-performance optimisation

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The ILD, International Large Detector, is one of the detector concepts for a future linear collider. Its performance is investigated using Monte-Carlo full simulation and PandoraPFA. Among several options, a combination of the silicon-tungsten electromagnetic calorimeter (SiW ECAL) and the semi-digital hadronic calorimeter (sDHCAL) presenting the highest granularity calorimeters, is here investigated. It is shown that by reducing the radius and length of the entire detector by a factor of ~ 1.3 with respect to the baseline dimensions, the jet energy resolution is degraded by 8 to 19% in the range of 45 and 250 GeV. The price of ILD which scales roughly quadratically with the ILD dimensions may be reduced by a factor of nearly two. A similar study made with the SiW ECAL and the analog hadronic calorimeter (AHCAL) shows that for an inner radius of ECAL of about 1.4 m, the performance is comparable between sDHCAL and AHCAL.

1 Introduction

The International Large Detector (ILD) concept [1, 2], combining an excellent tracking and a fine granular calorimetry system, has been optimised for particle flow approach (PFA) [3, 4]. The calorimetry system is composed of an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL). The ECAL consists of interleaved layers of absorbing material (tungsten) whereas the HCAL uses steel as absorber. There are two candidates for active material for both ECAL and HCAL. For ECAL one considers to use silicon sensors or scintillator plastic strips. For the HCAL, scintillator tiles and gaseous devices are proposed, respectively readout in analogue and semi-digital modes, the so-called AHCAL and sDHCAL.

A first estimation of cost of the ILD has been presented in the letter of intent for ILD [1]. It has been carefully revisited in the detailed baseline design [2]. In the latter it was estimated that the total cost of ILD can reach ~ 400 MILCU.^a

^aILCU is a common unit for ILC cost estimation, which is defined as 1 United State official currency, USD, on 1 January 2007.

The cost estimation for individual components of the full detector has shown that the most expensive parts are the return yoke and the SiW ECAL.

During the last few years, many studies have been performed on the optimisation of the cost-performance. For the SiW ECAL the cost is proportional to the silicon surface which is of about 2400 m² in the baseline design of ILD. In a recent study we have shown a possibility of reducing the number of layers (for a fixed number of radiation length, $23X_0$), cf. [2].

We consider here the feasibility of reducing the whole ILD size, i.e. radius and length proportionally. A similar study have been done for the ILD as a combination of SiW ECAL and AHCAL, cf. [4]. We concentrate only on the option of using silicon sensors for ECAL (SiW ECAL) and gas as active materials for HCAL (sDHCAL). For the SiW ECAL, a granularity of 5×5 mm² is chosen for the silicon sensor size. The gaseous detector HCAL is based on Glass Resistive Plate Chamber (GRPC) technology. The option of 1×1 cm² cells was chosen in a study on full ILD detector model is a compromise between a few mm cell size a better energy resolution provided by and the handling (and cost) of a huge number of electronic readout channels. The sDHCAL is readout in semi-digital mode, where the energy information is coded in 2-bit corresponding to three thresholds. This helps to correct the saturation effect and improve the energy resolution at high energies.

The list of softwares which are used for the analysis chain is listed in section 2 together with the simulation, calibration and jet energy reconstruction procedures. Section 3 discusses the ILD performance in terms of jet energy resolution. Some cross-checks are shown in section 4. And finally, all the results are summarized in section 5.

2 Simulation and reconstruction

2.1 Simulation

For the simulation, we use Mokka [5], an overlayer of GEANT4 version 9.5 [6], allowing for a complete parametrised geometry of ILD. The process

$$e^+ + e^- \rightarrow Z \rightarrow q\bar{q} \quad (1)$$

where Z is generated at rest at different centre-of-mass energies, 91, 200, 360 and 500 GeV is used. Only light quarks ($q = u, d, s$) are considered for the time being. For the modelling of hadronic showers, the Geant4 physics list QGSP_BERT has been used. This physics list is based on the Precompound model of nuclear evaporation [7] (QGSP) for high energy interactions, and the Bertini (BERT) cascade model [8] for intermediate energy interactions.

The radius and the length of the detector are changed proportionally such that their ratio is kept like in the baseline design. The modelled ECAL inner radii ($R_{\text{ECAL}}^{\text{inner}}$) and barrel lengths are given in table 1 together with the corresponding outer radius of the Time Projection Chamber (TPC), $R_{\text{TPC}}^{\text{outer}}$. All other parameters of ILD are kept unchanged, e.g. ECAL, sDHCAL segmentation, thicknesses ($23X_0$ and $6\lambda_I$), cell size.

$R_{\text{ECAL}}^{\text{inner}}$ (mm)	1843	1600	1400	1200
$R_{\text{TPC}}^{\text{outer}}$ (mm)	1808	1565	1365	1165
half length (mm)	2350	2040	1785	1530

Table 1: Parameters for different ILD configuration.

Events are reconstructed within the standard ILC Marlin [9] framework, version 01-16. The jets are reconstructed by the Pandora particle flow reconstruction algorithms, version 00-09, which was first developed in [4, 10] and its recent updates and improvements are presented in [11].

2.2 Calibration

To achieve best results with Pandora, it should be recalibrated for every ECAL inner radii. The calibration procedure is carried out in the following steps:

- determination of ECAL and HCAL hit conversion factors between deposited charge and energy; the factors for ECAL are determined using γ 's at 10 GeV, whereas for the sDHCAL the parameters have been determined for sDHCAL prototype in semi-digital mode using pion's of energies in the range of 5 and 80 GeV, cf. [12] for more details;
- hadron calibration: the initial ECAL and HCAL calibration parameters in the first step are determined for single particles. However, as hadrons in jets are a mixture of K_L 's, neutrons and anti-neutrons, these parameters need to be retuned to minimise the Monte-Carlo jet energy resolution. Two scaling parameters are defined: the weights which should be applied to the energy deposits in the ECAL and in the HCAL being identified as part of the hadronic showers. The minimisation is done through a scanning procedure by changing these two weights in order to search for a minimum of jet energy resolution. It is found that the ECAL energy weight should be 1.05 and 1.25 for the HCAL weight for all of ILD setups in this study;
- MIP calibration: determine the conversion factor from calorimeter hit to a minimum ionising particle (MIP) equivalent. This calibration step is done using μ^- 's at 10 GeV;
- angular correction: the energy lost in the gaps between modules in the barrel regions, and between module parts are currently not taken into account by reconstruction software. It is necessary to do a correction to compensate the lost energy. For the gaseous sDHCAL the angular correction also account for the varying sampling fraction. The correction is determined separately for γ 's and K_L^0 's by adjusting the mean value of the PandoraPFA reconstructed energy distribution for each bin of $|\cos\theta_q|$. Then it is applied to photons' and neutral particles in jets. An improvement of the resolution by about 2% in most of cases was observed, compared to the jet energy resolution without correction.

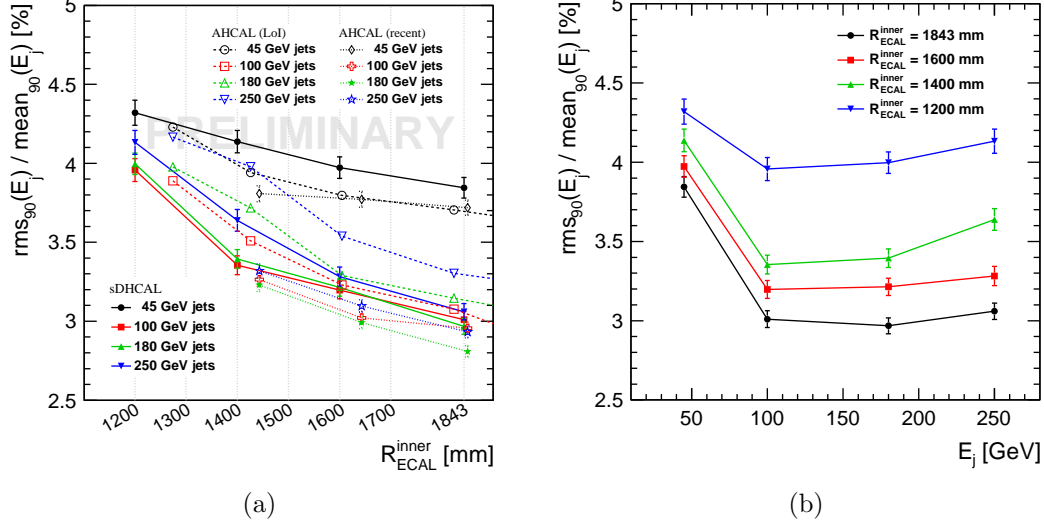


Figure 1: (a) Single jet energy resolution presented as a function of ECAL inner radius for jet energies between 45 and 250 GeV, and for three studies: SiW ECAL and AHCAL as published in the ILD LoI (dashed line), a similar study with recent version 0.12 of PandoraPFA (dotted lines), and SiW-ECAL+sDHCAL, with PandoraPFA version 0.09 (solid lines). (b) Single jet energy resolution shown as a function of simulated jet energy for different radii. Only statistical errors are shown.

3 Jet energy resolution

Jet energy resolution (JER) is a key estimator of the performance of ILD since it is related to the separation of hadronic decays of W and Z bosons through the reconstruction of their di-jet invariant masses. The di-jet energy, E_{jj} , is then summed up from single particle energies. The jet energy resolution is estimated by RMS90 method, which is the root mean square of the smallest energy range containing 90% of the events. The single jet energy resolution (SJER) is then defined as:

$$\frac{\text{RMS}_{90}(E_j)}{\text{mean}_{90}(E_j)} = \frac{\text{RMS}_{90}(E_{jj})}{\text{mean}_{90}(E_{jj})} \times \sqrt{2} \quad (2)$$

where the $\text{RMS}_{90}(E_{jj})$ and the $\text{mean}_{90}(E_{jj})$ are the RMS and the mean value of the distribution of dijet energy, E_{jj} . These are calculated from the total reconstructed energy distribution. To avoid the gap between the barrel and the endcap regions of the detector, only jets in the barrel region are considered.

Figure 1a shows the single jet energy resolution as a function of detector radius for three cases:

- ILD as a combination of SiW ECAL ($5 \times 5 \text{ mm}^2$ silicon cell size) and AHCAL (analog HCAL, with $3 \times 3 \text{ cm}^2$ tiles) as reported in the ILD Letter of Intent [1],
- similar study but with version 00.12 of Pandora, cf. [13],

- this study, where ILD consists of SiW ECAL and sDHCAL ($1 \times 1 \text{ cm}^2$ cell size). The total thicknesses, cell size, number of layers of ECAL and HCAL and other parameters are kept constant.

In the first two cases, only the radius is reduced whilst in the latter case, the radius and the length of ILD are kept proportional. The jet energy resolution degrades significantly by 11% and 14%, for jets at 100 and 250 GeV, correspondingly, if we choose to reduce the radius (and length) from 1843 mm (baseline design) to about 1400 mm. In the first two cases and especially for jet energies at 45 GeV, there is an important difference between PandoraPFA's versions (0.09 versus 0.12), i.e. the difference in resolution between two radii $R = 1.8 \text{ m}$ and $R = 1.4 \text{ m}$ is negligible with a recent release of PandoraPFA. For jet energies in the range of 100 to 180 GeV, the performances of the AHCAL and the sDHCAL are comparable at $R \sim 1.4 \text{ m}$.

The jet energy resolution is also shown as a function of simulated jet energies in Figure 1b for different ILD dimensions. At different detector sizes, the resolution behaves similarly: at low energy (45 GeV), the resolution is rather poor, this is due to the fact that the performance is dominated by intrinsic calorimeter resolution; for jet energies above 100 GeV, the resolution starts to degrade due to the *confusion*, i.e. mistakes in assignment of the energies to the different reconstructed particles, especially charged and neutral particles.

From Figure 1a, it can be seen that the jet energy resolution at $R_{\text{ECAL}}^{\text{inner}} = 1.2 \text{ m}$ is significantly worse than for $R_{\text{ECAL}}^{\text{inner}} = 1.4 \text{ m}$. The latter seems to be the minimal radius acceptable in ILD. This has to be confirmed by studies around this value, with other parameters (number of layers in SiW ECAL, wafer size, ...)

4 Further checks

A few cross checks have been made to verify the results.

4.1 Magnetic fields

To study how the magnetic field affects jet energy resolution, we choose $R_{\text{ECAL}}^{\text{inner}} = 1.4 \text{ m}$ and vary the magnetic field $B = 3.15, 3.5$ (default), $3.85, 4.20$ and 4.55 Tesla. The obtained single jet energy resolution, is shown in Figure 2a. For 45 GeV jets, for $B \geq 3.5 \text{ T}$, the resolution does not change significantly. This can be explained by the fact that the resolution at 45 GeV or less than 100 GeV is dominated by intrinsic calorimeter resolution. As the B-field increases, there is a trade-off between the loss of low transverse momentum tracks in the beam-pipe and improvement of the measurement of the remaining ones. For higher energies, especially at 250 GeV, the resolution improves with B.

4.2 Effect of tracking on jet energy resolution

By reducing the ECAL inner radius, and hence the TPC radius, the tracking performance may degrade, it is therefore important to quantify how it affects the PFA performance. The comparison between the default reconstruction and the reconstruction when the track energies are taken to be the true Monte-Carlo (MC) values

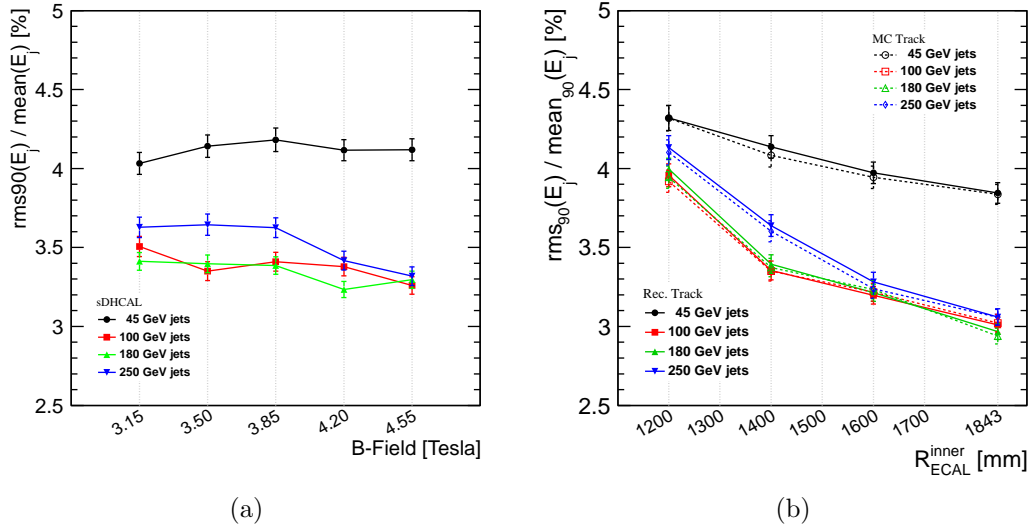


Figure 2: Checks of magnetic field and tracking effect on jet energy resolution. (a) Single jet energy resolution as a function of magnetic field for $R_{\text{ECAL}}^{\text{inner}} = 1.4$ m. (b) Single jet energy resolution as a function of ECAL inner radius for two cases: with default tracking reconstruction (solid curves) and with MC truth tracks (dashed curves). Slight difference observed due to changes in tracking.

are shown in Figure 2b. The very small difference observed demonstrates that the track reconstruction does not affect the final Pandora performance.

4.3 sDHCAL in analog mode

As mentioned above, the sDHCAL sensors are GRPC and the energy estimation is based on hit counting using semi-digital mode which helps to correct the saturation effect in gas. For a confirmation, the sDHCAL is simulated as an analog calorimeter, i.e. taking the energy deposits proportional to the charge deposits. The analysis procedure is then performed as was done for the AHCAL. For jet at 45 GeV, we found the corresponding resolution is about 4.23% which is significantly worse than what is obtained by the semi-digital mode.

5 Summary

The relation between dimension and performance is studied for ILD using the combination of highest granularity calorimeters, $5 \times 5 \text{ mm}^2$ cell size for the silicon-tungsten electromagnetic calorimeter (SiW ECAL) and $1 \times 1 \text{ cm}^2$ for the semi-digital hadronic calorimeter (sDHCAL) using detailed GEANT4 models and full reconstruction of $Z \rightarrow q\bar{q}$ events, with the Z decaying at rest.

Different ILD models are investigated by varying the ECAL inner radius. The length is modified proportionally in order to keep the same ratio as in the detailed baseline design. It has been shown that the reconstructed jet energy resolution may degrade by about 8 to 19% for simulated jet energies in the range of 45 and 250 GeV

$R_{\text{ECAL}}^{\text{inner}}$ (mm)	E_j (GeV)			
	45.6	100	180	250
	RMS ₉₀ (E_j)/ E_j (%)			
1843	3.85	3.01	2.97	3.06
1400	4.14	3.35	3.39	3.64

Table 2: Jet energy resolution for different jet energies, 45.6, 100, 180, 250 GeV, and for two values of radius: 1843 and 1400 mm.

if the radius is reduced from 1.8 m to 1.4 m, cf. Table 2. Nevertheless, the models with $R_{\text{ECAL}}^{\text{inner}} \sim 1.4$ m still meet the ILC jet energy resolution goals, $\sigma_E/E < 3.8\%$. The price of ILD scaling roughly quadratically with the ILD dimensions may reduce by a factor of nearly two. It is also shown that $R_{\text{ECAL}}^{\text{inner}} \sim 1.4$ m seems to be minimal radius acceptable for ILD.

The comparison to a similar study for the SiW ECAL and the analog hadronic calorimeter (AHCAL) shows that the ILD performance is comparable for these two options of HCAL at $R_{\text{ECAL}}^{\text{inner}} \sim 1.4$ m.

The study on the effect of tracking on the final jet energy resolution leads to the conclusion that the modification of ILD size may affect the tracking performance but this does not have significant impact on the PFA performance. It is shown that for $R_{\text{ECAL}}^{\text{inner}} = 1400$ mm, there is possibility to increase slightly the magnetic field to compensate the degradation due to the reduction of the detector dimension, mostly at high energies (250 GeV jets).

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